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101 East 27th Street
Suite 5.300
Austin, TX 78712 -1532

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| | | | | | 512-471-4186 |

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# RPPR Final Report
as of 23-Oct-2017

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**Agreement Number: W911NF-13-1-0463**

**INVESTIGATOR(S):**


**Name:** PhD Jayant Sirohi
**Email:** jayant.sirohi@mail.utexas.edu
**Phone Number:** 5124714186
**Principal:** Y

Organization: **University of Texas at Austin**
Address: 101 East 27th Street, Austin, TX 787121532
Country: USA
DUNS Number: 170230239
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**Report Date:** 30-Jun-2017
Date Received: 11-Aug-2017
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**Title:** Detailed Measurements of the Aeroelastic Response of a Rigid Coaxial Rotor in Hover
**Begin Performance Period:** 23-Sep-2013
**End Performance Period:** 31-Mar-2017
**Report Term:** 0-Other


Submitted By: PhD Jayant Sirohi
Email: jayant.sirohi@mail.utexas.edu
Phone: (512) 471-4186


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**STEM Degrees:** 3
**STEM Participants:** 3

**Major Goals:** The goal of this project is to measure the performance, steady and vibratory loads, and blade deformation of a rigid, coaxial counter-rotating (CCR) rotor in hover. The modal characteristics of the blades in the rotating frame will be extracted from the blade deformation measurements. The transient loads and blade deformation occuring due to passage of upper and lower rotor blades will also be measured. These data will be useful for validation of computational models of CCR rotor systems and will yield an understanding of the physical phenomena occurring during interaction of upper and lower rotor blades.

**Accomplishments:** Experiments performed over the course of this project included: hover testing of single and CCR rotors (Year 1), deformation measurement and modal identification of rotor blades in the non-rotating and rotating conditions (Year 2), and measurement of transient loads due to blade passage of upper and lower rotors (Year 3).
The rotor test setup including transmission, instrumentation and rotor blades were all designed and fabricated in-house at UT Austin. The structural and inertial distributions of the rotor blades, as well as the detailed experimental data were shared with Dr. Rajneesh Singh and Dr. Hao Kang at Vehicle Technology Directorate (VTD), Aberdeen Proving Grounds, MD. In this way, the experimental data could be used to validate US Army comprehensive analysis tools, specifically CFD/CSD coupled analysis Helios. The data was also shared with researchers at University of Maryland (UMD) and Technische Universitat Munich (TUM). The validated analyses could then be used to design CCR rotors with reduced vibratory loads.

**Training Opportunities:** Nothing to Report

**Results Dissemination:** Please see uploaded report

**Honors and Awards:** Nothing to Report

**Protocol Activity Status:**

**Technology Transfer:** The structural and inertial distributions of the rotor blades, as well as the detailed experimental data were shared with Dr. Rajneesh Singh and Dr. Hao Kang at Vehicle Technology Directorate (VTD), Aberdeen Proving Grounds, MD.

**PARTICIPANTS:**

# RPPR Final Report
as of 23-Oct-2017

**Participant Type:** PD/PI
**Participant:** Jayant Sirohi
**Person Months Worked:** 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Christopher Cameron
**Person Months Worked:** 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Daiju Uehara
**Person Months Worked:** 7.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)
**Participant:** Sergio Rizo-patron
**Person Months Worked:** 7.00 **Funding Support:**
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Date Received: 10-Aug-2017 Conference Date: 20-May-2014 Date Published: 20-May-2014
Conference Location: Montreal, Canada
**Paper Title:** Performance and Vibratory Hub Loads of a Mach-Scale Coaxial Rotor in Hover
**Authors:** Christopher Cameron, Anand Karpatne, Jayant Sirohi
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**Paper Title:** Transient Hub Loads and Blade Deformation of a Mach-Scale Coaxial Rotor in Hover
**Authors:** Christopher G. Cameron, Daiju Uehara, Jayant Sirohi
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**Paper Title:** Computational and Experimental Study of Coaxial Rotor Steady and Vibratory Loads
**Authors:** Rajneesh Singh, Hao Kang, Mahendra Bhagwat, Christopher Cameron, Jayant Sirohi
Acknowledged Federal Support: **Y**

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Conference Location: Ft. Worth, TX
**Paper Title:** Measurement of Transient Loads and Blade Deformation in a Coaxial Counter-Rotating Rotor
**Authors:** Christopher Cameron, Jayant Sirohi, Roland Feil, Juergen Rauleder
Acknowledged Federal Support: **Y**

**DISSERTATIONS:**

**Publication Type:** Thesis or Dissertation
**Institution:** The University of Texas at Austin
Date Received: 10-Aug-2017 Completion Date: 12/10/15 7:12PM
**Title:** Operational modal analysis of a rotating cantilever beam using high-speed Digital Image Correlation
**Authors:** Sergio Rizo-Patron
Acknowledged Federal Support: **N**

**Project Summary - Grant # W911NF-13-1-0463**

**(Reporting Period: September 2015 – August 2016)**

# FINAL REPORT: Detailed Measurements of the Aeroelastic Response of a Rigid Coaxial Rotor in Hover

Jayant Sirohi
Department of Aerospace Engineering and Engineering Mechanics,
The University of Texas at Austin,
Austin, TX 78712

## Objective

The goal of this project is to measure the performance, steady and vibratory loads, and blade deformation of a rigid, coaxial counter-rotating (CCR) rotor in hover. The modal characteristics of the blades in the rotating frame will be extracted from the blade deformation measurements. The transient loads and blade deformation occuring due to passage of upper and lower rotor blades will also be measured. These data will be useful for validation of computational models of CCR rotor systems and will yield an understanding of the physical phenomena occurring during interaction of upper and lower rotor blades.

## Approach

a) Measure the steady and vibratory loads of a reduced-scale (80 inch diameter) CCR rotor system with stiffened blades over a range of hover conditions.

b) Develop a technique to measure the deformation of the rotating blades using high-speed Digital Image Correlation.

c) Extract the modal properties of the blades in the non-rotating condition (excited by an electromagnetic shaker) and during rotation (excited by a jet of air).

d) Measure the transient loads and transient blade deformation during the upper and lower rotor blade passage.

e) Share the measured loads, blade deformation and extracted modal properties with VTD (Aberdeen Proving Grounds, MD) for validation of their CFD/CSD models.

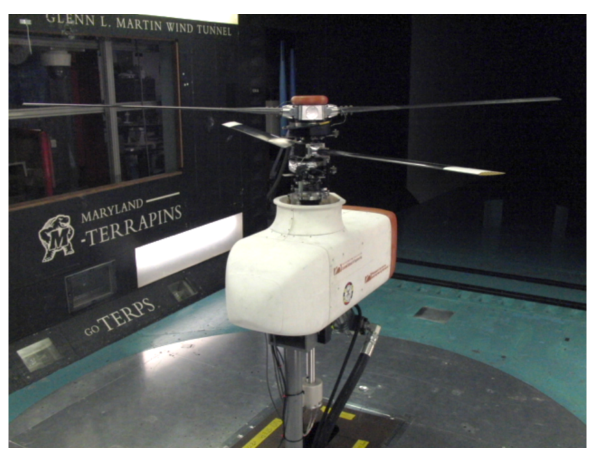

*Figure 1. Reduced-scale CCR rotor system undergoing forward flight tests in the Glenn Martin Wind Tunnel.*

## Relevance to Army

The compound helicopter configuration, with a rigid CCR rotor, is a contender for the Joint Multi-role Rotorcraft (JMR). Development of next-generation rotorcraft with CCR rotor systems requires high-fidelity analytical tools. Experimental data collected over the course of this research project was used to validate Army analytical tools such as RCAS and Helios (published in AIAA Papers #2015-2884 and #2016-1787); agreement of steady loads was within 5% while the vibratory loads differed by up to 50%. The investigations in this project were complementary to those performed under the Vertical Lift Research Center of Excellence (2011-2016) Task A1.4, in which the same CCR rotor system was tested in forward flight in the Glenn Martin Wind Tunnel at advance ratios of up to 0.5 and lift offset up to 20% (Fig. 1).

Accurate prediction of vibratory loads requires detailed measurement of the aeroelastic response of the rotor blades, especially their modal properties. In this project, a non-contact method to extract the rotating natural frequencies of rotor blades was developed. In addition, a comprehensive set of benchmark data was collected; these data can be used to validate analytical tools. The transient loads and blade deformation experiments performed in this project will be instrumental in achieving the goal of understanding and alleviating vibration in rigid rotor systems.

**Summary of important results**

Experiments performed over the course of this project included: hover testing of single and CCR rotors (Year 1), deformation measurement and modal identification of rotor blades in the non-rotating and rotating conditions (Year 2), and measurement of transient loads due to blade passage of upper and lower rotors (Year 3).

The rotor test setup including transmission, instrumentation and rotor blades were all designed and fabricated in-house at UT Austin. The structural and inertial distributions of the rotor blades, as well as the detailed experimental data were shared with Dr. Rajneesh Singh and Dr. Hao Kang at Vehicle Technology Directorate (VTD), Aberdeen Proving Grounds, MD. In this way, the experimental data could be used to validate US Army comprehensive analysis tools, specifically CFD/CSD coupled analysis Helios. The data was also shared with researchers at University of Maryland (UMD) and Technische Universitat Munich (TUM). The validated analyses could then be used to design CCR rotors with reduced vibratory loads.

Hover test results:

Hover testing of 2-bladed single (isolated) rotors, 4-bladed single rotors and 2-bladed (each) CCR rotor systems were performed in the first year of this project. These experiments were focused on the performance of the rotor system, especially the thrust sharing between rotors and their mutual interference. Analytical fits to the performance data, obtained from momentum theory, showed that the CCR rotor system required approximately 6% less power than the equivalent single rotor system having identical disk area and solidity (Fig. 2). In addition, the experiments showed that the upper rotor produced approximately 55% of the total CCR rotor thrust, irrespective of the total thrust magnitude. Experimental results were used to validate a free vortex wake model of the single and CCR rotor systems; the validated model was then used to investigate the breakdown between induced and profile power of the rotors as well as radial variation of inflow.

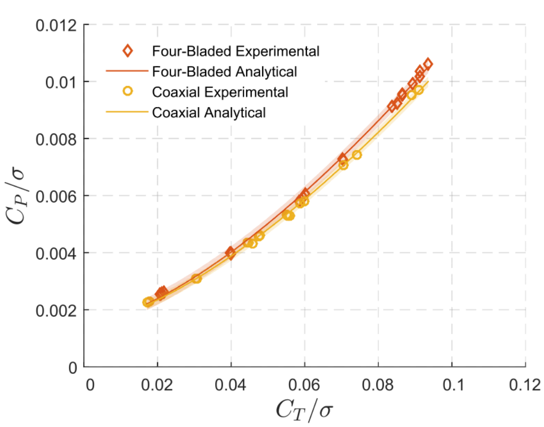


*Figure 2. Comparison of isolated single rotor performance with CCR rotor performance.*

The hover tests also revealed information about the vibratory loads of the CCR rotor system. Dominant 4/rev vibratory hub loads

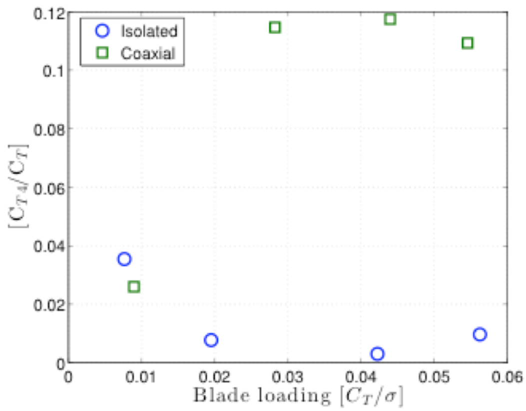

*Figure 3. Ratio of 4/rev vibratory thrust to mean thrust, coaxial two-bladed rotor system compared to isolated four-bladed single rotor system.*

were measured, caused by interaction between the upper and lower 2-bladed rotors at each blade crossing. Figure 3 shows that the magnitude of the 4/rev thrust load in the CCR rotor system is approximately 11% that of the mean thrust of an isolated single rotor with the same solidity.

The large vibratory loads provided further impetus for the remainder of the project, specifically focusing on dynamic calibration of the load cell and modal identification of the rotor blades.

Deformation measurement and modal identification:

The deformation of the rotor blades in the non-rotating as well as rotating conditions was measured using a non-contact optical technique called Digital Image Correlation (DIC). In this technique, a stochastic speckle pattern is painted on the blade surface, and two high-speed cameras take images of the deformed blades as a function of time (Fig. 4). In conjunction with a calibration procedure, and images of the undeformed rotor blade, the images from the two cameras are used to calculate the deformation of the rotor blade at each time instant. During Year 2 of the project, low-speed cameras were used to measure phase-averaged deformation of the rotor blades at different rotation speeds and collective pitch angles. As part of the Vertical Lift Research Center of Excellence (2011-2016) Task A-1.4, these data were used to validate a comprehensive analysis code (UMARC).

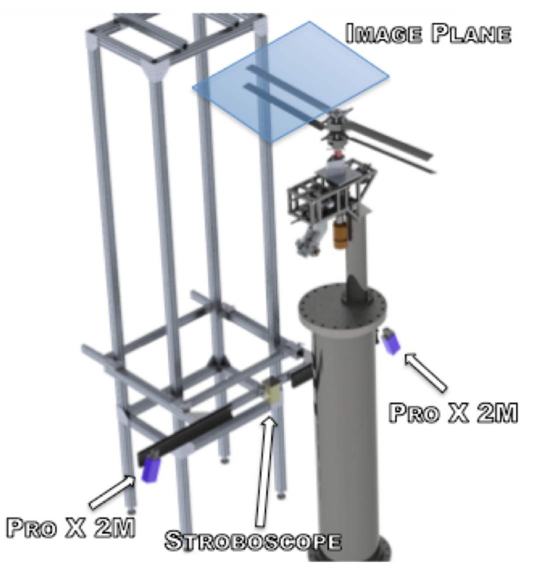

*Figure 4. Setup for measurement of blade deformation using Digital Image Correlation.*

Figure 5 shows the image captured by the cameras and the calculated deformation of the lower rotor blade. The deformation of the isolated rotor blade and CCR rotor blade is shown in Fig. 6.

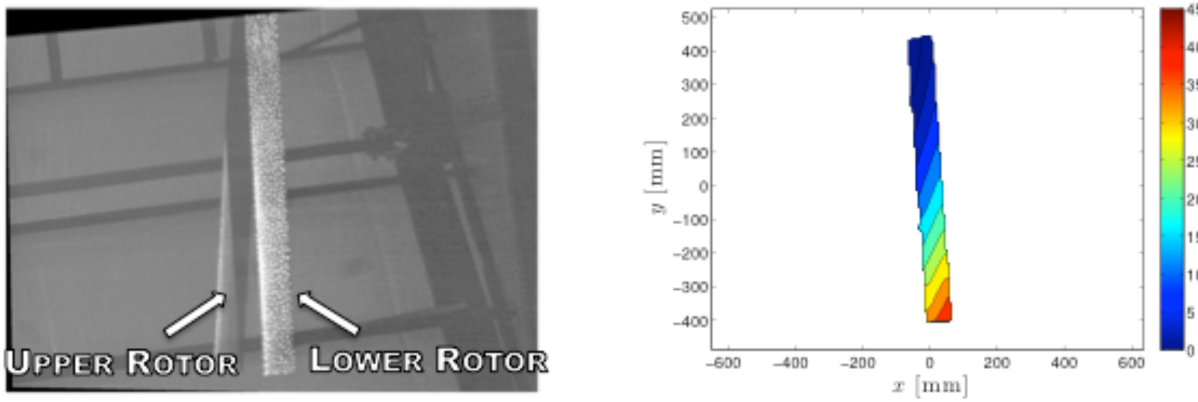


*Figure 5. Raw image captured by cameras (left) and bending deformation of lower blade calculated by DIC (right).*

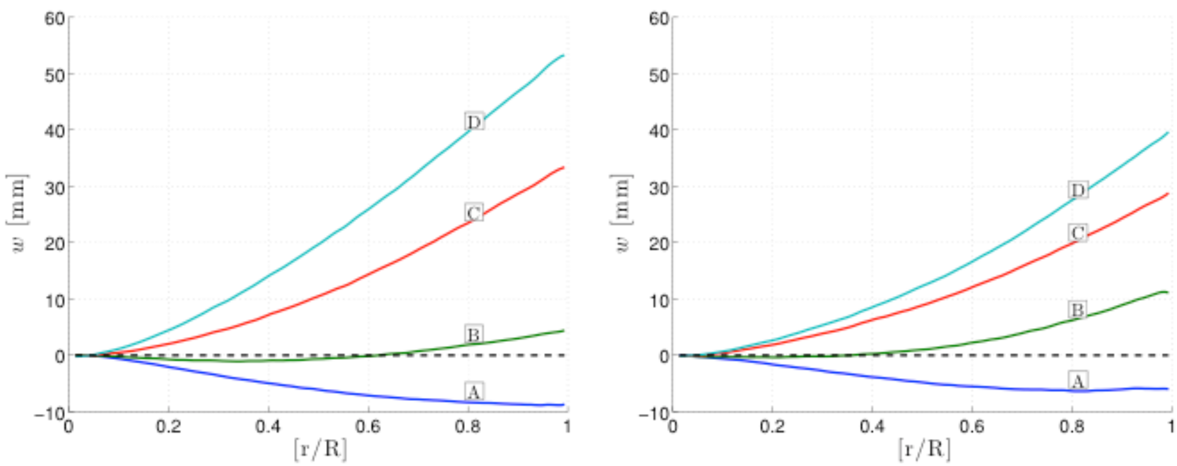


*Figure 6. Rotor blade bending deformation. Isolated single rotor is shown on the left and lower rotor of the CCR rotor system is shown on the right. Cases A, B, C, D correspond to the same blade loadings.*

In Year 3, the methodology of measuring the deformation of rotating blades and extracting modal parameters was further refined. A single-bladed rotor was tested in hover and the blade was excited by a jet of compressed air (Fig. 7). High-speed digital cameras were used for time-resolved blade deformation measurements, and the modal parameters were extracted using a modified Ibrahim Time Domain (ITD) method and Eigenstructure Realization Algorithm (ERA). The same blade was also rigidly clamped at the root and excited by a shaker; the same approach was used to capture images, extract deformation and identify modal parameters. The analyses were able to extract not only the natural frequencies of the rotor blade in the rotating and non-rotating condition, but also the mode shapes. The measured natural frequencies were compared to predictions from a finite element numerical model of the

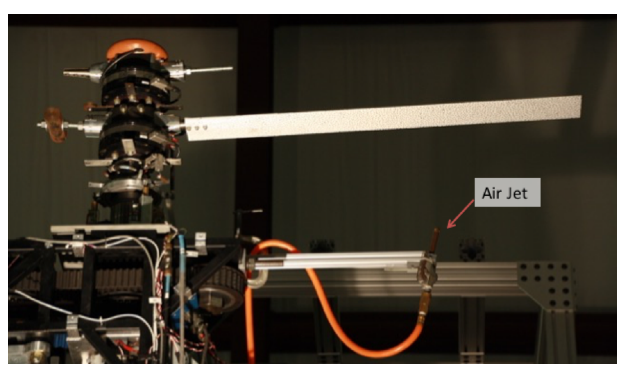


*Figure 7. Single-bladed rotor with out-of-plane excitation provided by air jet.*

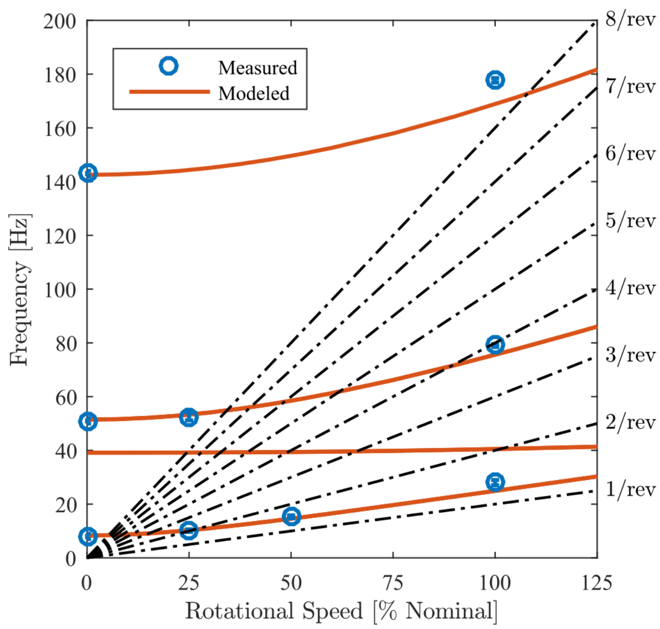


*Figure 8. Rotor blade natural frequencies as a function of rotor speed.*

rotor blade; good agreement was observed especially at the lower modes. At the higher modes, the amplitude of vibration was significantly smaller than for the lower modes, and this resulted in a lower signal to noise ratio and reduced confidence in the identified mode. Therefore, there is more discrepancy between the measured and modeled natural frequency for the higher modes (as shown in Fig. 8).

The identified natural frequencies and mode shapes will be used to validate CFD/CSD coupled analyses by specifying the structural deformation. In this way, the CFD part of the analysis can be independently validated.

Measurement of transient loads due to blade passage of upper and lower rotors:

To measure the transient loads due to blade passage, a CCR rotor system was assembled with a single blade per rotor, balanced by a counterweight (Fig. 9). In this way, vibratory loads due to blade dissimilarities were eliminated. The loads were measured using the hub-mounted load cells and the transient deformation of the lower rotor blade as the upper blade passed over it was measured using the high-speed cameras.

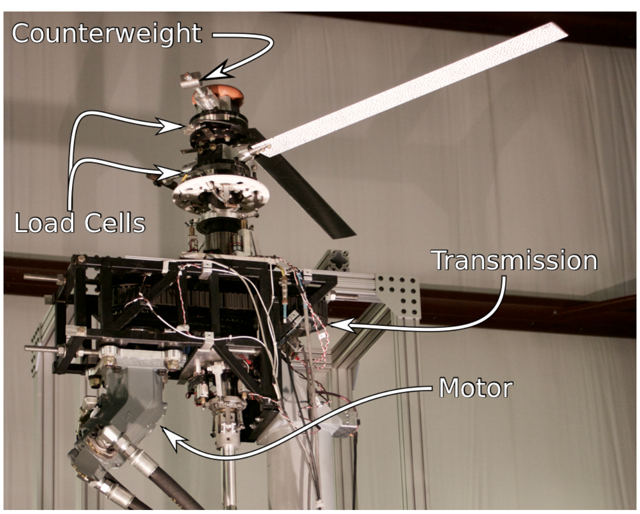


*Figure 9. CCR rotor system with single-bladed rotors and counterweight.*

The measured hub loads as well as push-rod loads showed significant vibration at higher harmonics. Therefore the measured loads were filtered to keep only a few harmonics of rotor speed. The measured lower rotor hub load and lower rotor push-rod force are shown in Fig. 10; the shaded region represents an uncertainty in the measurements after phase-averaging over 100 revolutions.

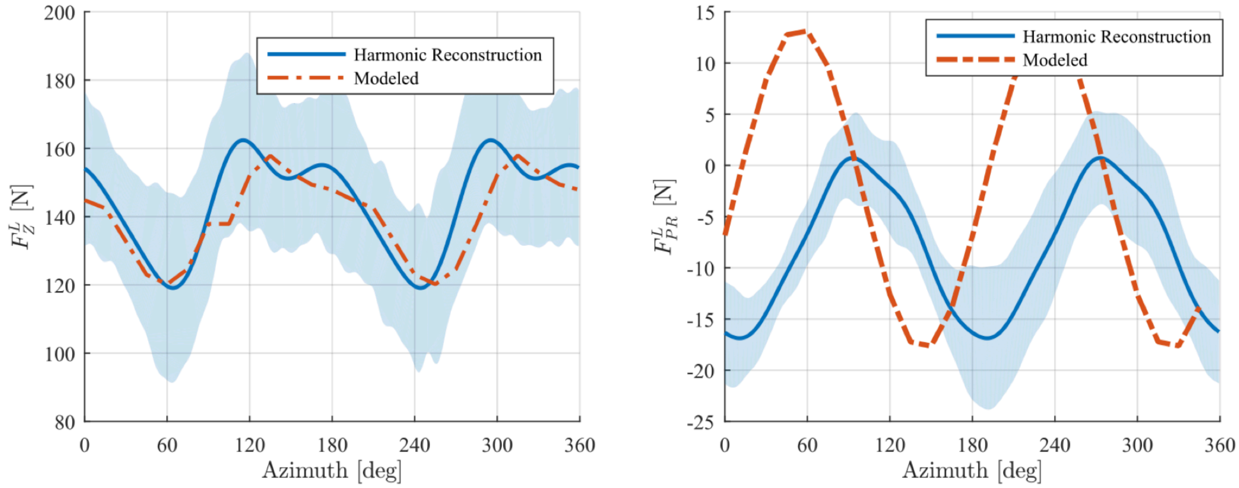


*Figure 10. Measured lower rotor hub load and push-rod load, compared with model predictions.*

It can be seen that the amplitude of the vibratory load is about 14% of the mean thrust, which is a significant for a single-bladed rotor. The comprehensive analysis (TU Munich) is able to predict the hub load but is not able to predict the push-rod load properly. At present, investigation of this discrepancy is ongoing and the measured blade natural frequencies and mode shapes will be used to validate the aerodynamic model.

## Conclusions

This project has resulted in a unique data set as well as measurement methodology. The performance as well as steady and vibratory loads of isolated single rotors and CCR rotor systems has been measured. The structural and inertial properties of the rotor blades have been measured and documented. A novel non-contact deformation measurement system has been developed and used to extract rotor blade rotating frame modal properties. These data have been shared with researchers at VTD, UMD and TUM to further the development of coupled comprehensive analysis tools. The analyses are able to predict the performance and steady loads very accurately, and investigations into the correlation of vibratory loads, especially in the push-rods, is ongoing. The validated analyses can be used to improve the design of CCR rotor systems with reduced vibrations.

One PhD degree and three M.S. degrees have been awarded to students funded by this project. Two archival journal articles and four refereed conference papers have resulted from work done during this project. Out of these, two papers are being refined and submitted for publication in archival journals.

### Journal articles


1) Cameron C., Karpatne A. and Sirohi J., "Performance of a Mach-scale Coaxial Counter-rotating Rotor in Hover", Journal of Aircraft, Vol. 53, No. 3, May 2016, pp. 746—755.

2) Rizo-Patron S. and Sirohi J., "Operational Modal Analysis of a Helicopter Rotor Blade Using Digital Image Correlation", J. Exp Mech (2017) 57: 367-375.


### Conference papers


1) Cameron C., Karpatne A. and Sirohi J., "Performance and Vibratory Hub Loads of a Mach-Scale Coaxial Rotor in Hover", AHS International 70th Annual Forum, Montreal, Canada, May 20-22, 2014.

2) Singh R. and Kang H., “Computational Investigations of Transient Loads and Blade Deformations on Coaxial Rotor Systems”, AIAA Paper #2015-2884, 33rd AIAA Applied Aerodynamics Conference, 22-26 June 2015, Dallas, TX.

3) Cameron C., Uehara D. and Sirohi J., “Transient Hub Loads and Blade Deformation of a Mach-Scale Coaxial Rotor in Hover”, AIAA Paper 2015-1412, 56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Kissimmee, Florida, 5-9 January 2015.

4) Singh R., Kang H., Bhagwat M., Cameron C. and Sirohi J., “Computational and Experimental Study of Coaxial Rotor Steady and Vibratory Loads”, AIAA Paper 2016-1787, 54th AIAA Aerospace Sciences Meeting, San Diego, California, 4-8 January 2016.

5) Feil R., Rauleder J., Hajek M., Cameron C. and Sirohi J., “Computational and Experimental Aeromechanics Analysis of a Coaxial Rotor System in Hover and Forward Flight” 42nd European Rotorcraft Forum, Lille, France, 6–8 September, 2016.

6) Cameron C., Sirohi J., Feil R., and Rauleder J., “Measurement of Transient Loads and Blade Deformation in a Coaxial Counter-Rotating Rotor”, AHS International 73rd Annual Forum, Fort Worth, Texas, USA, 9-11 May, 2017.

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